TECHNICAL NOTES

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THE TIME LAG AND INTERVAL OF DISCHARGE WITH A SPRING ACTUATED FUEL INJECTION PUMP.

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This paper deals with some research on a spring actuated fuel pump for solid or airless injection with small, high speed internal combustion engines. The pump characteristics under investigation were:

(1) The interval of fuel injection in terms of degrees of crank travel and in absolute time.

(2) The lag between the time the injection pump plunger begins its stroke and the appearance of the jet at the orifice.

(3) The manner in which the fuel spray builds up to a maximum when the fuel valve is opened, and then diminishes.

Equipment and Procedure.

The equipment consisted of (1) a vertical, single cylinder, 4-stroke cycle engine which was motored over during the runs; (2) a spring actuated plunger pump, with 7/32 in. diameter lapped plunger, supplied with gas oil by a gear primary pump; (3) an injection nozzle.

The injection pump plunger was actuated during the discharge stroke by a heavy coil spring. The spring, enclosed in a guide, was previously compressed by means of spiral cam acting through a follower and rocker arm. The cam had a radial drop. The discharge stroke began when the follower on the cam came to this drop; an adjustable stop controlled the length of plunger stroke. Hence the following data are for an injection pump always having the same maximum pressure behind the plunger at the beginning of each stroke, but with diminishing pressure as length of stroke (and of spring) increased. The effort exerted by the spring at the end of the plunger stroke could decrease as much as 10 to 20%, depending upon the length of plunger stroke used. (See calibration curve of pump plunger spring.) Thus with a spring actuated pump the speed of plunger during its discharge stroke is independent of engine speed.

Since the injection pump regulated the quantity of fuel for each shot, the nozzle was designed to open automatically under a given oil pressure at which the spring on the nozzle valve stem was set. Runs were made at spring settings as low as 2200 lbs. and as high as 5000 lbs. per square inch. These settings were obtained with a different spring in each case. The following table refers to the springs used:

Pressure to lift valve	Dia. wire in spring	Outside dia. coils	Number of free coils
2200 ±	.0808	0.50 in.	3 1/2
3200 ±	.106	0.50 in.	2 1/2
5000 ±	.106	0.51 in.	1 1/2

The pressure required to lift the nozzle valve was determined on a gage testing machine. The $\pm$ signs are added because this method of opening and seating a valve is not comparable with the rapid opening and closing in actual service where the thickness of oil film under the valve, and hence the ease in opening the valve, may differ from what obtains with the slow operation of the gage tester. The heavier springs were imperfect in that the axis of the coils was not a straight line. As a result of this and since the spring guide clearance was such as to permit possible side thrust on valve stem, the friction of the valve stem may not have been the same for all three springs. However, the valve stem sleeve was of such length as to minimize binding.

The nozzle had a single small orifice. Four different orifice diameters were tried: 0.012 in., 0.014 in., 0.018 in., and 0.022 in The nozzle valve seat was close to the orifice. Hence there was but little fuel between seat and orifice.

The tabulated data were obtained from paper "targets." These consisted of strips of soft paper cut to the curvature of the side of the flywheel rim; and attached thereto with shellac, which was allowed to dry only sufficiently to hold the paper against the centrifugal force of its own mass. The nozzle was firmly attached to the engine frame in such a manner that the orifice faced and was but a small fraction of an inch from the paper, and lay in a vertical plane through the crank pin position when at top dead center. The discharge, therefore, left a pattern on the paper as the flywheel rim rotated past the nozzle.

These patterns represent actual discharge conditions with engine under power except that there was more fuel to be compressed because this nozzle location required a longer fuel line between nozzle and pump. There was, besides, a slight lag between the time of the appearance of the jet at the orifice and its contact with the paper, due to the gap which the spray had to cross. By making this gap under 3/16 inch, the error in readings on the target due to this lag, was made smaller than the error experienced in determining the precise limits of the pattern on the target.

A run consisted in first motoring the engine at the desired speed and adjusting the pump stroke. During this time, the spray was kept from hitting the paper target by means of a sheet iron deflector. The deflector was suddenly withdrawn for an interval of from 3 to 10 seconds, depending on strength of spray, and again replaced. The trail of the spray on the paper target was measured in terms of degrees of crank movement with respect to T.D.C. (top dead center).

Most of the targets were well marked by a distinct cutting. With the larger sized orifices the paper was often cut clear through. For other than the heaviest portions of the discharge, the surface of the paper was usually furred; the clearness of the furring depended upon the number of discharges against the paper, the size of the orifice, and the variation in the discharge during the interval. While the beginning of impact was usually well defined, the exact termination of the furring upon clean paper was often vague. In order to make the readings more definite the paper was rubbed with fine dry graphite.

Interpretation of Data.

In the absence of photographic records of the patterns made by the spray, no definite information can be presented of the rate of build-up and decline of the discharge. The targets showed, in general, a short "build up" period of the jet; then a sudden blast when the nozzle valve reached its maximum lift, followed by a more or less constant rate of discharge, after which followed an interval of reducing flow while the nozzle valve was seating. Difficulties of interpreting the patterns always lay with the trailing end. An interval of from 4 to 10° of crank travel was sufficient for the discharge to become intense.

As might be expected from a spring actuated pump, the smaller the orifice, the more nearly did the targets show a period of somewhat uniform discharge. The variation in the rate of discharge, as shown by all the patterns, made clear the futility of attempting to assume even approximately correct values for discharge coefficients for such interrupted flow, or of placing reliance on determinations based on the hydraulic equation $V = \sqrt{2gh}$. Actual change in the rate of discharge during each pump cycle could have been determined only by collecting and weighing the discharge for equal increments of crank travel. Apparatus for such determinations was not at the time available, and hence no attempts have been made to deduce discharge coefficients from the tabulated data.

Where there is more than a degree or two of difference between results from the same conditions, it may be attributed to a difference in decision as to whether a furred portion of the pattern or what appeared as only a wetted portion of the pattern, indicated a true limit of the discharge interval. Thus the pattern may appear longer than the true impact interval because of some flow of the fluid after impact. Further, a weak trailing edge may take many shots to show a pattern as compared with few required for the heavy portion of the discharge.

Lag.

The variation in the lag of the jet after beginning of plunger stroke, as deduced from Table II, shows:

(1) For a given stroke and orifice, the lag increases with fuel pressure in nearly every case. This would be expected because of the greater amount of compression of the fuel and elasticity of the injection system before the nozzle valve yielded to the injection pressure.

(2) For a given stroke and pressure, the lag increases with increase in size of orifice in six out of nine of the groups of data. This may be due to the pressure in the line between the pump discharge valve and the nozzle valve dropping to a lower pressure during discharge because of less resistance through the orifice. Hence on next injection more of the plunger stroke would be used in restoring the pressure and overcoming elasticity in line.

(3) For a given pressure and orifice, the data is not sufficiently conclusive to make deductions on the change in the lag with the stroke.

<u>Discharge Interval</u>.

The variation in discharge interval with pressure, stroke and orifice, as deduced from Table III, shows:

(1) For a given stroke and orifice the discharge interval decreases with pressure in seven out of nine groups of data.

(2) For a given stroke and pressure the discharge interval decreases with increase in orifice.

(3) For a given pressure and orifice the discharge interval increases with stroke in eight out of nine groups of data.

<u>Timing of Injection</u>.

Except for runs 79, 80 and 81, all the targets were made at 1600 R.P.M. and with the plunger stroke beginning 92° before T.D.C. With a lag of 20 to 25°, the spray appears at about 70° before T.D.C. This early injection would appear to invite preignition if applied to actual operation. But at 1600 R.P.M., 70° of crank travel is a brief period. Also the time at which ignition occurs, with compression ignition, depends not alone on when injection begins but on when sufficient fuel has vaporized to create a combustible mixture at the necessary compression pressure and temperature. In actual operation pump cam setting as early as 92° before T.D.C. was found necessary with the smaller nozzles.

In so far as the injection system is concerned, the time of injection will depend on (1) the degree of atomization; (2) rate of fuel discharge; and (3) distribution.

The actual timing of injection is governed by the tendency to preignition on the one hand and late burning and low M.E.P. on the other. It follows that the available time for fuel evaporation is a fundamental consideration in obtaining reasonable capacity with compression ignition. Hence, besides showing how long injection occurs the data has been extended, by calculations, to show the time available for the evaporation of the first and last portions of the fuel that enter the cylinder per cycle. As an extreme limit it was arbitrarily chosen that all the fuel should be injected and vaporized by the time the crank is 40° past T.D.C.

Little is known of the time necessary for the vaporization of the fuel. Even when most finely divided some interval must elapse between the entrance of the fuel and its complete vaporization. Since all the fuel cannot be injected instantaneously, injection at the speeds of airplane engines (1600 to 2200 R.P.M.) must begin early in order to get capacity. But how early? The answer calls for research on the rate of fuel vaporization. Upon that research, rather than upon the trial of mechanical devices, may depend the determination of the attainable R.P.M. and M.E.P. of high speed engines running on compression ignition.

TABLE I.

Diameter of orifice .012 R.P.M. 1600

No. of run	Fuel Press	Pump Stroke	Beginning of Pattern.	Lag of Spray	Injection Interval		Time for fuel to vaporiza.		REMARKS.
					Crank degree	Seconds	First Part	Last Part	
1	2800±	1/8	72	20	68	.00708	.0117	.00462	Heavy for 12°, light portion at 25° from beginning.
2		1/8	70	22	66	.00687	.0115	.00463	
3		3/16	72	20	108	.0113	.0117	.0004	Light for last half of pattern.
4		3/16	72	20	107	.0112	.0117	.0005	Rapidly diminishing pattern for last 15°.
5		1/4	71	21	124	.0129	.0116	-.0013	Gradual lightening but definite trailing end.
6		1/4	70	22	125	.0130	.0115	-.0015	
7		5/16	71	21	150	.0156	.0116	-.0040	Definite trailing end.
8		5/16	71	21	150	.0156	.0116	-.0040	
9	3200±	1/8	69	23	45	.00469	.0114	.00671	Light near middle, then heavier until near end.
10		1/8	69	23	45	.00469	.0114	.00671	Similar to No.59.
11		3/16	68	24	89	.00929	.0113	.00201	Evidence of nozzle valve fluttering.
12		3/16	70	22	78	.00813	.0115	.00337	Target of harder paper, required more shots to cut paper.
13		3/16	68	24	76	.00792	.0113	.00338	Abrupt start and finish, fairly even pattern.
14		1/4	70	22	108	.0113	.0115	.0002	10° to heaviest pattern, heavy for 40°, light for last 55°.
15		1/4	69	23	104	.0108	.0114	.0006	
16		1/4	69.	23	103	.0107	.0114	.0007	Light for 6° after first 30°, light for last 25°.
17		5/16	66	26	104	.0108	.0110	.0002	Heavy for first 30°, light until within 10° of trailing end.
18		5/16	69	23	113	.0118	.0114	-.0004	Evidence of nozzle valve fluttering.
19		5/16	67	25	124	.0129	.0111	-.0018	10° to heaviest pattern, heavy for 60°.
20		5/16	68	24	124	.0129	.0113	-.0016	Light for last 45°.

TABLE I (Contd.)

Diameter of orifice .012 for runs 21 to 26;
" " " .014 " " 27 " 32.

R.P.M. 1600

No. of run	Fuel Press	Pump Stroke	Beginning of Pattern.	Lag of Spray	Injection Interval. Crank degree	Injection Interval. Seconds	Time for fuel to vaporize. First Part	Time for fuel to vaporize. Last Part	REMARKS.
21	5000±	3/16	65	27	55	.00573	.0109	.00517	Heavy for 2/3 pattern, washed for 11° beyond recorded measurement.
22		3/16	66	26	55	.00573	.0110	.00527	Washed for 12° beyond recorded measurement.
23		1/4	62	30	78	.00813	.0106	.00247	5° before heaviest pattern, heavy to within 15° of trailing end.
24		1/4	62	30	78	.00813	.0106	.00247	
25		5/16	63	29	98	.0102	.0107	.0005	5° to heaviest pattern, heavy for 2/3 pattern, gradually diminishing pattern.
26		5/16	62	30	97	.0101	.0106	.0005	Light for last 25°.
27	2200±	3/16	67	25	89	.00928	.0110	.00182	
28		3/16	67	25	90	.00938	.0111	.00172	Light pattern at middle.
29		1/4	65	27	109	.0114	.0109	-.0005	Heavy for first 70°.
30		1/4	63	29	103	.0107	.0107	.0000	Well defined trailing end.
31		5/16	71	21	119	.0124	.0116	-.0008	Heavy for first 70°, target too short.
32		5/16	71	21	132	.0138	.0116	-.0022	Heavy for first 70°.

TABLE I (Contd.)

Diameter of orifice .014 R.P.M. 1600

No. of run	Fuel Press	Pump Stroke	Beginning of Pattern.	Lag of Spray	Injection Interval. Crank degree	Injection Interval. Seconds	Time for fuel to vaporize. First Part	Time for fuel to vaporize. Last Part	REMARKS.
33	3200±	3/16	64	28	65	.00667	.0108	.00403	Began coating targets with dry graphite to give better definition of trailing end.
34		3/16	63	29	68	.00709	.0107	.00361	
35		3/16	63	29	58	.00604	.0107	.00466	
36		3/16	63	29	62	.00646	.0107	.00424	Target washed for 30° beyond recorded measure with indication of flutter in this period.
37		1/4	63	29	62	.00646	.0107	.00424	Discharge interrupted for about 1° (jump
38		1/4	61	31	71	.00740	.0105	.00310	
39		1/4	63	29	70	.00730	.0107	.00340	Splashes of 20° with 2° jump.
40		1/4	63	29	61	.00635	.0108	.00445	
41		1/4	68	24	73	.00760	.0113	.00370	
42		1/4	66	26	72	.00750	.0110	.00350	
43		1/4	68	24	66	.00688	.0113	.00442	
44		1/4	66	26	68	.00709	.0110	.00391	
45		5/16	62	30	113	.0118	.0106	-.00120	
46		5/16	60	32	111	.0116	.0104	-.00120	Pattern light for last 33°.

TABLE I (Contd.)

Diameter of orifice .014 for runs 47 to 52;
" " " .018 " " 53 " 62.

R.P.M. 1600

No. of Run	Fuel Press	Pump Stroke	Beginning of Pattern	Lag of Spray	Injection Interval		Time for fuel to vaporize.		REMARKS.
					Crank degree	Seconds	First Part	Last Part	
47	5000±	3/16	60	32	46	.00479	.0104	.00561	4° before heaviest pattern, heavy for 2/5 of pattern, light for last 3°.
48		3/16	59	33	43	.00448	.0103	.00582	Similar to No. 47.
49		1/4	60	32	75	.00781	.0104	.00259	5° before heaviest pattern, heavy for 3/5 of pattern, light for last 10°.
50		1/4	61	31	75	.00781	.0105	.00269	Similar to No. 49.
51		5/16	57	35	78	.00813	.0101	.00197	5° before heaviest pattern, heavy for 1/2 pattern, abrupt stop tp trailing end.
52		5/16	56	36	79	.00824	.0100	.00176	Heavy for 1/2 pattern, fairly heavy to within 5° of trailing end.
53	2200±	1/8	77	15	30	.00312	.0122	.00908	Cut through paper for 4° at middle.
54		1/8	70	22	23	.00240	.0105	.00810	Distinct rebound.
55		1/8	70	22	22	.00229	.0105	.00821	Distinct rebound.
56		3/16	71	21	49	.00510	.0106	.00550	Heavy for 1/2 pattern, rapidly diminishing pattern.
57		3/16	70	22	46	.00479	.0105	.00571	Similar to No. 61.
58		3/16	70	22	45	.00469	.0105	.00581	
59		1/4	66	26	55	.00573	.0110	.00527	6° to heaviest pattern, jump at middle, gradually diminishing pattern.
60		1/4	66	26	55	.00573	.0110	.00527	Evidence of flutter near middle of pattern
61		5/16	67	25	53	.00552	.0111	.00558	6° to heaviest discharge, 10° heavy pattern, paper cut through for 8°, then light portion, heavy portion and short diminishing pattern.
62		5/16	66	26	54	.00562	.0110	.00538	Cut through paper and shellac where heavy, diminishing pattern for last 10°.

TABLE I (Contd.)

Diameter of orifice .018 R.P.M. 1600

No. of run	Fuel Press	Pump Stroke	Beginning of Pattern	Lag of Spray	Injection Interval: Crank degree	Injection Interval: Seconds	Time for fuel to vaporize: First Part	Time for fuel to vaporize: Last Part	REMARKS.
63	3200±	1/8	65	27	50	.00520	.0109	.00570	Difficult to detect limits of pattern, evidence of fluttering.
64		3/16	61	31	28	.00292	.0105	.00758	Heaviest cut in pattern after about 6° and before 18°.
65		3/16	63	29	28	.00292	.0107	.00778	
66		1/4	63	29	30	.00312	.0107	.00758	Light for last 8°.
67		1/4	60	31	27	.00281	.0104	.00759	
68		5/16	60	32	33	.00344	.0104	.00696	6° to heaviest pattern, cut through paper to within 4° of end.
69		5/16	59	33	30	.00312	.0103	.00718	
70	5000±	1/8	59	33	26	.00271	.0103	.00759	Difficult to detect limits of discharges.
71		1/8	61	31	22	.00229	.0105	.00821	Difficult to detect limits of discharges.
72		3/16	52	40	20	.00208	.00958	.00750	Washed for 8° before recorded measurement then 4° to heaviest pattern, then cut through to within 5° of end.
73		3/16	52	40	23	.00240	.00958	.00718	Washed for 8° before recorded measurement.
74		1/4	51	41	29	.00302	.00946	.00644	3° to heaviest pattern, paper cut through to within 3° of end.
75		1/4	50	42	28	.00292	.00938	.00646	Washed for 5° before recorded measurement.
76		5/16	61	31	53	.00552	.0105	.00498	10° to heaviest pattern, cut through for 20°, gradually diminishing pattern.
77		5/16	51	41	42	.00437	.00946	.00509	Target washed for 10° before recorded measurement.
78		5/16	51	41	43	.00448	.00946	.00498	Paper cut through from 5° after start to 4° before end of pattern.

TABLE I (Contd.)

R.P.M. 1700 for run 79
" 1400 " " 80 & 81
" 1600 " " 82 & 83

Diameter of orifice .022

No. of run	Fuel Press	Pump Stroke	Beginning of Pattern	Lag of Spray	Injection Interval Crank degree	Injection Interval Seconds	Time for fuel to vaporize. First Part	Time for fuel to vaporize. Last Part	REMARKS.
79	2200±	1/4	48	28	46	.00479	.00916	.00437	Discharge heavy for first 20°, apparent fluttering of nozzle valve. Pump stroke began 76° before T.D.C. in runs Nos. 79, 80, 81.
80		1/4	52	24	43	.00448	.00957	.00509	Discharge heavy for first 20°.
81		1/4	52	24	42	.00438	.00957	.00519	Discharge heavy for first 20°.
82	3200±	1/4	57	35	15	.00156	.0101	.00854	Pump stroke began 92° before T.D.C.
83		1/4	55	37	15	.00156	.00989	.00833	Duplicated No. 4.

1. Fluttering of nozzle valve stem on its seat is shown on target by alternate heavy and light portions of pattern in rapid succession during discharge interval.

2. Where a minus sign occurs before a value of the vaporization period, it indicates that injection continues beyond the arbitrarily chosen 40° limit.

3. The fuel used was Diesel Engine Oil (gas oil) with a specific gravity of .858 at 60° F.

4. An idea of the small quantity of fuel discharged per cycle, (with slip of pump = 0) may be gained from following tabulation.

Dia. pump plunger = 7/32 in.

Stroke	1/8	3/16	1/4	5/16
Volume of fuel. cu.in.	.0047	.00705	.0094	.0117
Diam. of equiv. sphere. in.	.224	.256	.282	.304

TABLE III.

Variation of Discharge Interval with Pressure and Diameter of Orifice.

Pump stroke 3/16 in. 1600 R.P.M. for engine: 800 R.P.M. for pump.

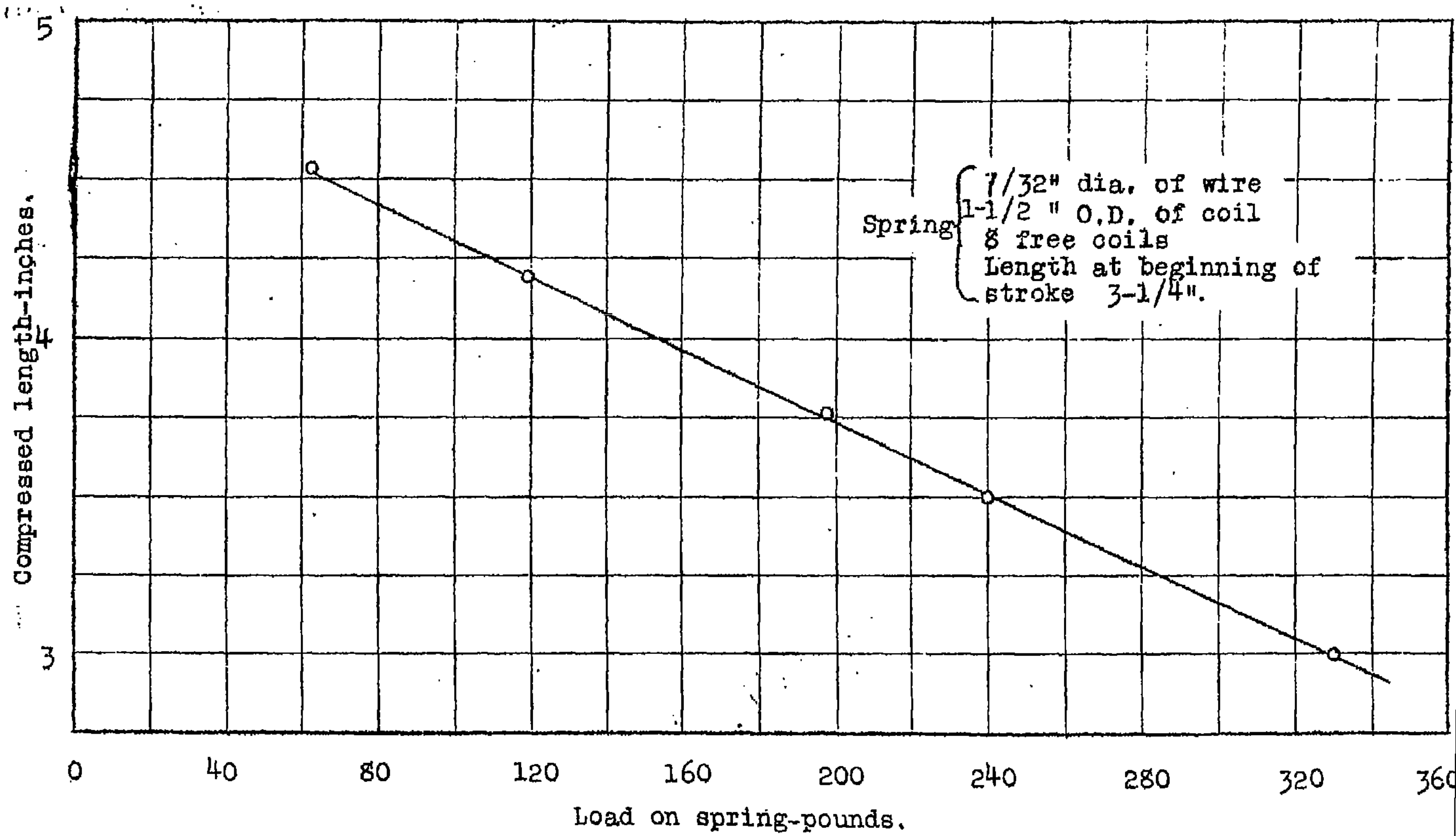
	PRESSURE								
	2200			3200			5000		
Orifice	.012	.014	.018	.012	.014	.018	.012	.014	.018
Run	3,4	27,28	56,57,58	11,12,13	33,36,34	64,65	21,22	47,48	72,73
Interval	107,108	89,90	49,46,45	89,78,76	65,62,68	28	55	46,43	20,23
	Pump stroke 1/4 in. 1600 R.P.M. for engine: 800 R.P.M. for pump.								
Orifice	.012	.014	.018	.012	.014	.018	.012	.014	.018
Run	5,6	29,30	59,60	16,15,14	40,41	66,67	23,24	49,50	74,75
Interval	124,125	109,103	55	103,104,108	61,73	30,27	78	75	29,28
	Pump stroke 5/16 in. 1600 R.P.M. for engine: 800 R.P.M. for pump.								
Orifice	.012	.014	.018	.012	.014	.018	.012	.014	.018
Run	7,8	31,32	61,62	17,19	45,46	68,69	25,26	51,52	76,77
Interval	150	119,132	53,54	104,124	113,111	33,30	98,97	78,79	53,42

TABLE II.

Variation in Lag with Pressure and Diameter of Orifice.

Pump stroke 3/16 in. 1600 R.P.M. for engine: 800 R.P.M. for pump.

	PRESSURE								
	2200			3200			5000		
Orifice	.012	.014	.018	.012	.014	.018	.012	.014	.018
Run	3,4	27,28	56,57,58	11,12,13	33-36	64,65	21,22	47,48	72,73
Lag	20	25	21,22	24,22	28,29	31,29	27,26	32,33	40
	Pump stroke 1/4 in. 1600 R.P.M. for engine: 800 R.P.M. for pump.								
Orifice	.012	.014	.018	.012	.014	.018	.012	.014	.018
Run	5,6	29,30	59,60	14,15,16	37-44	66,67	23,24	49,50	74,75
Lag	21,22	27,29	26	22,23	31-24	29,31	30	32,31	4,42
	Pump stroke 5/16 in. 1600 R.P.M. for engine: 800 R.P.M. for pump.								
Orifice	.012	.014	.018	.012	.014	.018	.012	.014	.018
Run	7,8	31,32	61,62	17-20	45,46	68,69	25,26	51,52	76,77,78
Lag	21	21	25,26	26-23	30,32	32,33	29,30	35,36	31,41



Calibration of fuel pump spring.